Possible exploratory research on advanced, compact, heavy ion fusion power plants based on thick-liquid vortex chambers

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Synopsis:

We have adapted an idea of swirling vortex liquid walls for MFE [Ralph Moir "Liquid first walls for magnetic fusion energy configurations", Nuclear Fusion Vol 37, No. 4, April 1997, p 557] to a heavy ion inertial fusion chamber using a cusp-shaped swirling liquid Flibe wall to absorb the neutrons, in a geometry synergistic with a cusp magnetic field to guide and focus heavy ions onto the target. A single magnetic cusp field in the chamber center commonly focuses an annular array of heavy-ion beams to reduce the effective standoff distance of the final focusing system, thus allowing smaller target spot sizes. New low yield, high gain, close-coupled HIF target designs could then be utilized with driver energies as low as 1 MJ [D. Callahan, LLNL, private communication], allowing smaller IFE plant sizes. The magnetic field also guides ionized target debris axially along the solenoidal length, distributing the heat and reducing vaporization from the surface. Utilization of swirling thick liquid walls allows for a continually replenished liquid surface facing the target. A cusp-like liquid surface is obtained by driving a swirling liquid vortex into the interior of cylindrical structural shell from both sides, with an azimuthally symmetric outlet in the magnetic cusp region so that the liquid streams are ejected by their own centrifugal momentum. The radius of the first liquid surface is chosen large enough so that liquid fracture due to neutron isochoric heating is avoided, and the thickness of the liquid flow is chosen so damage in structural materials are reduced to an acceptable level. The reduction of vaporized and spalled wall material allows for faster chamber clearing and increased repetition rate.

Research is proposed to study the underlying heavy ion beam and target physics requirements, and liquid wall hydrodynamics issues, associated with this novel HIF chamber and focusing concept. The scheme relies on ballistic focusing of pre-stripped heavy-ions with current and space-charge-neutralization in a sufficiently high density ambient target debris plasma ($\sim 10^{15}$-10^{17} cm^{-3}). The plasma temperature and conductivity must be high enough before each beam pulse to prevent uncontrollable beam-self-pinching and filamentation. The hydrodynamics aspects related to formation of cusp are to be explored using commercial numerical hydrodynamic code package called Flow3d, a 3-D time-dependent Navier-Stokes Equation solver with a volume of fluid (VOF) free surface tracking algorithm. Relevant analysis on hydrodynamics and stability of swirling flows for novel MFE confinement schemes are also considered with these configurations.

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Goals:

Determine:

(1) The feasibility of focusing 40-50 GeV heavy-ions to 50 micron spots with close-in micro-plasma lens, through computer models and experiments using existing and planned upgrades of heavy-ion storage ring facilities around the world.

(2) The feasibility of using cusp magnetic fields to focus an annular array of heavy-ion beams to a close-coupled heavy-ion target.

(3) The feasibility of achieving CoE < 4 cts/kWehr with 4-unit plant outputs < 1200 MWe at 300 MWe/unit, using all-recycled parts and fluid vortex blankets to achieve high plant availability and virtually zero radioactive waste streams.

Advanced heavy-ion driven targets:

Fast ignition

The fast ignitor is an exploratory IFE concept in which ignition is accomplished by rapid injection of external heat after the fuel has been compressed to the required density (200-900 gm/cc). The ignition is so fast that the ignition region and main fuel can be far from pressure equilibrium. The ignition region by itself is inertially confined in this concept. For a given hot ignition zone $\rho r_{hot} \sim$ alpha range, the energy in the smaller, high density isochoric ignition zone is smaller than in the larger low density isobaric ignition zone by a factor of $\rho_{hot}^2 / \rho_{cold}^2$, and thus the target gain can be higher using fast ignition. Fig. 1 compares the DT fuel temperatures and densities for conventional ICF and fast igniter targets.

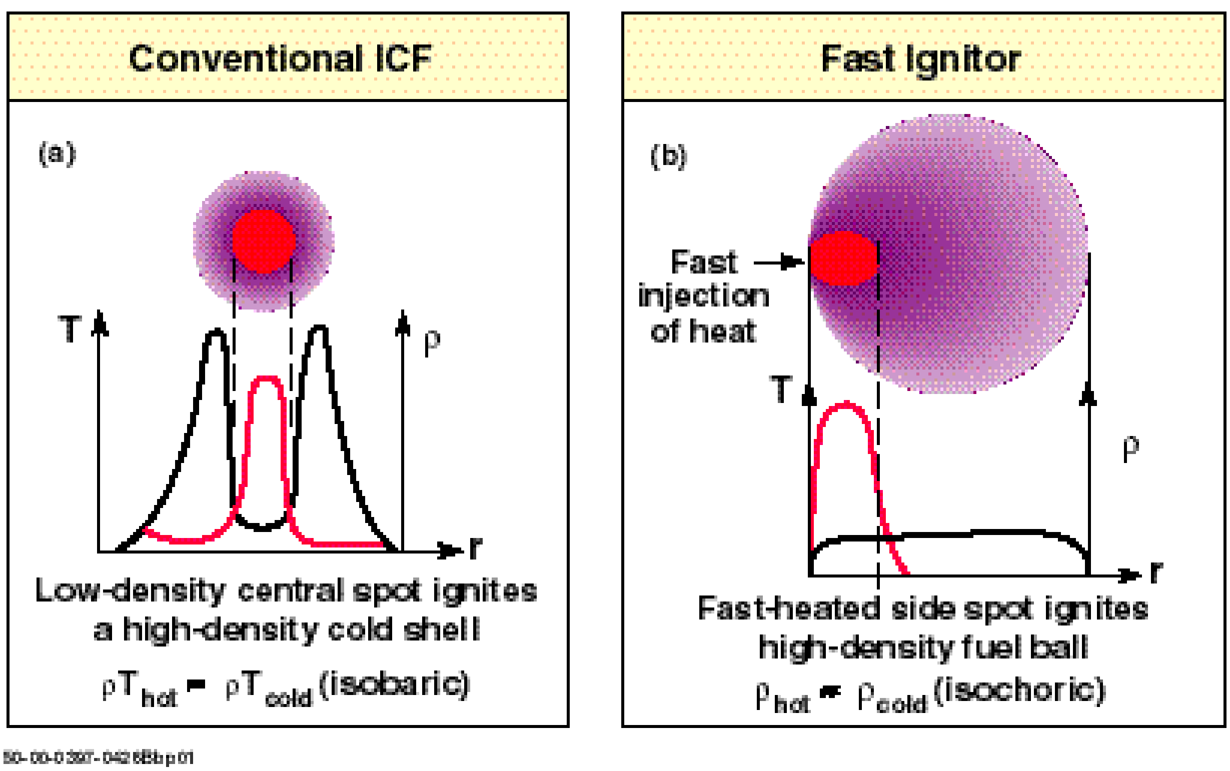

Fig. 1 Comparison of DT fuel temperature and density profiles for conventional ICF and fast-igniter targets.

Since the kinetic energy of the imploding shell can all go into fuel compression in the fast ignitor case, fast ignition supports either higher final ρr for a given implosion velocity v_{imp} and fuel mass M_{DT}, or allows lower ρ with larger r and M_{DT} for a given final ρr. The scheme is divided into three phases: First, the fuel is compressed conventionally. The driver can, in principle, be either a laser or an ion beam and the energy can be deposited either directly or indirectly via X-rays. Second, a path through the coronal plasma remaining from the implosion is bored with a laser beam with intensity about 10^{18} W/cm^2. Finally, a laser beam with intensity in the range 5 10^{19} - 5 10^{20} W/cm^2 couples 20kJ -100 kJ to the compressed fuel heating it to ignition. If a heavy-ion beam with the proper range can to focus to this intensity, it would be an ideal ignition driver because the ion energy deposits by classical dE/dx drag on electrons, with a peak energy deposition rate near the end of the ion range. After ignition, burn propagation and high gain follow. Simple models give the gain (driver energy) curve a factor 5-20 higher than the conventional ICF gain curves. Gain which is adequate for energy applications occurs with driver energy a factor 3-10 lower than the conventional schemes.

Close-coupled HIF targets

By shrinking the hohlraum closer to the capsule, the hohlraum-coupling efficiency can be effectively doubled, and therefore the HIF target gain can be twice as high as conventional HIF targets. [D. Callahan, LLNL, private communication]. The required beam spot sizes and pulse durations are also smaller, presenting a challenge to HIF accelerator designers, but not as stringent as for ion-driven fast ignition. Thus, this kind of advanced HIF target represents an intermediate possibility for small HIF power plants.

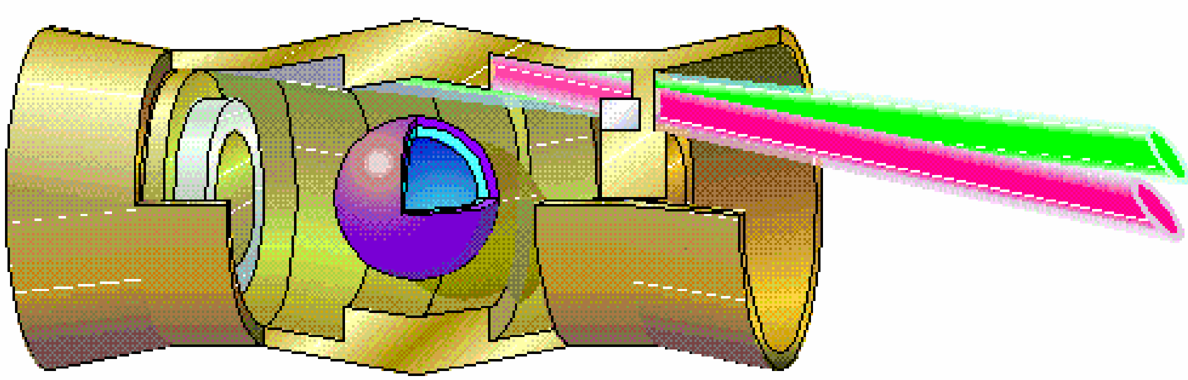

Fig. 2. Close-coupled HIF target : ~ 1MJ beam input, ~ 50 MJ yield, ~ 0.8 mm radius beam spots [D. Callahan, LLNL}

Chamber development for small, modular fusion power plants :

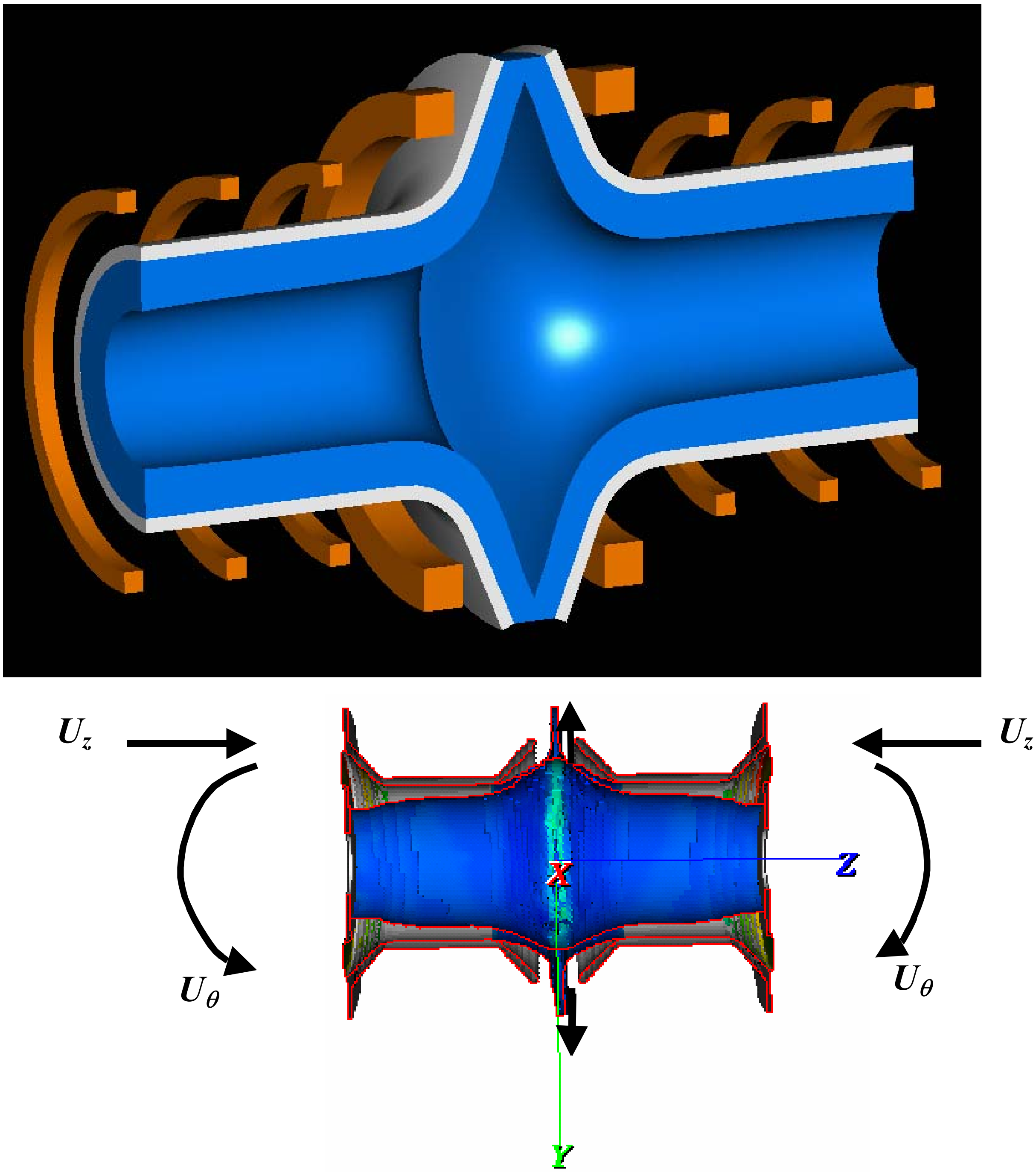

Fig. 3 General thick-liquid vortex chamber concept for advanced MFE and IFE concepts [After Abdou and co-workers, UCLA]. The flows are steady-state, with liquid swirling in from the ends and out the midplane for a symmetric cavity (lower image is a fully-3-D liquid flow simulation). The magnetic coils can be varied for magnetic confinement of MFE configurations, for heavy-ion beam focusing, or for target plasma debris diversion/conversion.

Opportunities for ion-driven advanced pulse-compression and focusing studies:

A near-term upgrade of the GSI heavy-ion storage ring is expected to deliver ~ 800 joules of ~40 GeV U^{28+} ions in ~30 ns FWHM pulses at one Hz to various target interaction experimental areas, focused by existing plasma lenses to ~ 1 mm spots by end of calendar 2000 (I. Hoffman, 97 International HIF Symposium, Heidelberg, Nuc. Instr. & Meth. In Phys. Res. A, Vol. 415, (1998) 11-19.). Further possible improvements:

1. Stronger bunch compression (velocity tilt) using induction modules instead of RF bunchers (Steve Lund is now at GSI working on this).
2. Reduction of space charge during drift pulse compression and final focusing using various methods of plasma neutralization.
3. Reduction of spot size through drastic reductions of plasma lens focal length using laser-driven megagauss micro-plasma lens. .

The rationale for this concept selected for advanced HIF, besides the cost-effectiveness of shared development costs with advanced MFE concepts, is that these advanced targets with driver energies as low as 1 MJ offers the best IFE opportunity to allow a small modular power plant with a low cost, low energy driver and still achieve adequate target gain for acceptable recirculating power fraction. With attendant low fusion yields below 50-100 MJ, an economical power output per unit (800 -1000 MW_{fus} per chamber) may require pulse rates too high (e.g., > 10 to 20 Hz depending on the yield per pulse) for chamber clearing by gravity or even by oscillating jets with a reasonable shielding thickness, liquid pumping power, and sufficiently close final optic stand-off distance.

To meet this challenge, the vortex flow must be able to run steady state without breakup or droplet ejection into the cavity. The low fusion yields made possible by fast ignition, and the effect of an embedded magnetic field to cushion the target debris expansion, is hoped to allow a reasonably compact (moderate cavity radius) vortex to operate steady-state with very low liquid pumping power. [A broken-up vortex may be difficult to flush and re-establish at 10 to 20 Hz, and the liquid pumping power can become unreasonable]. For MFE applications, a key issue is the plasma compatibility with the liquid vapor pressure from regions where the scrape-off layer may intersect with the liquid cavity surface. For IFE, the vapor pressure for beam propagation is no so much a concern as is avoidance of vortex breakup or droplet formation due to shocks driven into the liquid from each target. One can always scale up the radius and size to the point where breakup would not occur, but we seek a compact chamber for a small, modular, multi-unit plant with a shared driver and target factory. The three most critical issues to achieve this, aside from the demonstration of formation of steady state vortices thick enough to protect the chamber structure from (in order of energy release) neutrons, target debris, and x-rays:

1. What is the spinodal limit (the isochoric heating deposition limit) that would fracture the various liquids? This data is needed to determine the minimum vortex radius versus fusion yield per target necessary to avoid bulk breakup due to isochoric neutron heating. Laser-induced shock fracture can be used to measure this.
2. What are the magnetic field strengths and embedded fluxes in the vortex cavity that can divert the hot target plasma debris away from the liquid surface. The target blows

a beta=1 bubble which is RT unstable on the first bounce. Dimitri Ryutov has a colleague in Russia doing such an experiment, but one might also use various pulsed plasma guns to simulate this problem.

3. What cavity vapor pressure is consistent with beam propagation as well as x-ray pulse broadening and absorption to reduce x-ray-ablation driven shocks on the liquid surface. This was an issue studied in the Prometheus IFE power plant study.

Below shows an application of the liquid vortex chamber to an IFE concept for small modular power plants.

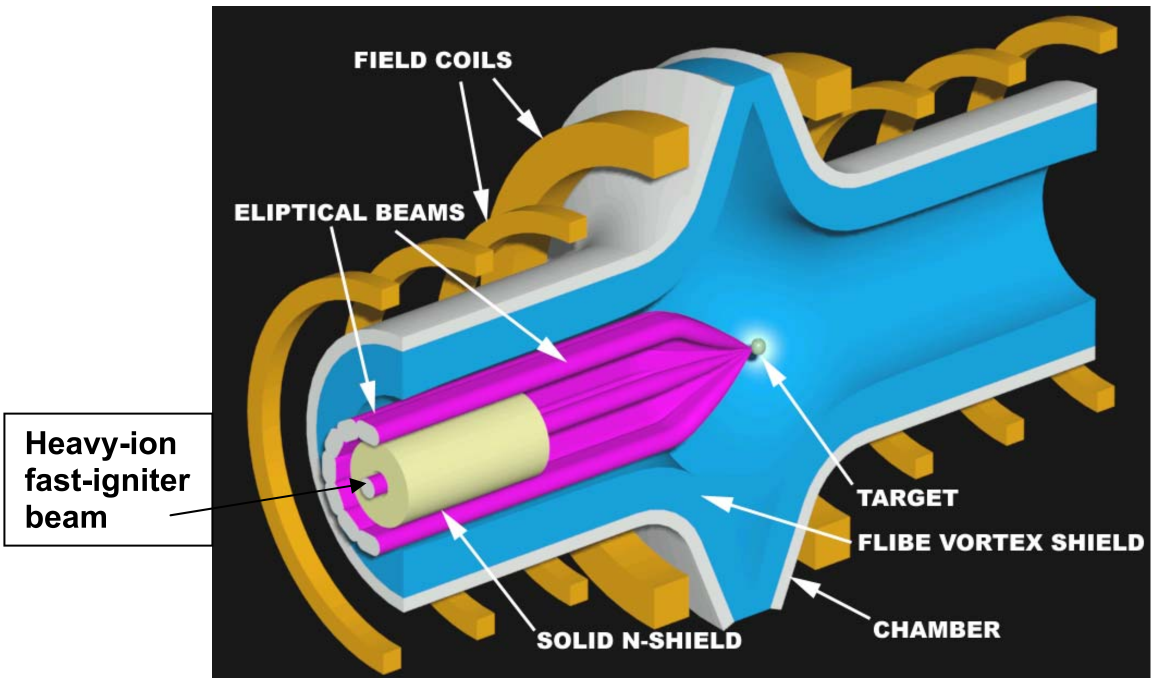

Fig. 4 Ion-driven fast-igniter or close coupled HIF target with vortex chamber. Coils focus annular compression beams, central igniter beam is focused with laser-driven micro-plasma lens. The central igniter beam is not needed in the case of close-coupled targets.